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Sea level change: a philosophical approach

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Abstract The present Cenozoic era is an 'icehouse' episode characterized by a low sea level. Since the beginning of the industrial revolution, the human race has been emitting greenhouse gases, increasing the global atmospheric temperature, and causing a rise in sea level. If emissions continue to increase at the present rate, average global temperatures may rise by 1.5 °C by the year 2050, accompanied by a rise of about 30 cm in sea level. However, the prediction of future climatic conditions and sea level is hampered by the difficulty in modelling the interactions between the lithosphere, kryosphere, biosphere and atmosphere; in addition, the buffering capacity of our planet is still poorly understood. As scientists cannot offer unambiguous answers to simple questions, sorcerer's apprentices fill in the gaps, presenting plans to save planet without inconveniencing us.

The geological record can help us to learn about the regulation mechanisms of our planet, many of which are connected with or expressed as sea level changes. Global changes in sea level are either tectono-eustatic or glacio-eustatic. Plate tectonic processes strongly control sea levels and climate in the long term. There is a strong feed-back mechanism between sea level and climate; both can influence and determine each other. Although high sea levels are a powerful climatic buffer, falling sea levels accelerate climatic accentuation, the growth of the polar ice caps and will hence amplify the drop in sea level. Important sources of fossil greenhouse gases are botanic CO_2 production, CO_2 released by volcanic activity, and water vapour. The latter is particularly important when the surface area of the sea increases during a rise in sea level ('maritime greenhouse effect'). A 'volcanogenic greenhouse effect' (release of volcanogenic CO_2) is possibly not equally important, as intense volcanic activity may take place both during icehouse episodes as well as during greenhouse episodes. The hydrosphere, land vegetation and carbonate platforms are major CO_2 buffers which may both take up and release CO_2. CO_2 can be released from the ocean due to changes in the pCO_2 caused by growth of coral reefs and by uptake of CO_2-rich freshwater from karst provinces. Efficient sinks of CO_2 are the weathering products of silicate rocks; long-term sinks are organic deposits caused by regional anoxic events which preferrably develop during sea level rises and highstands; and coal-bearing strata. Deposition of limestone also removes CO_2 from the atmospheric-hydrospheric cycle at a long term. Biotic crises are often related to either sea-level lows or sea-level highs. Long-term sea-level lows, characteristic of glacial periods, indicate cooling as major cause of extinction. During verly long-lasting greenhouse episodes the sea level is very high, climate and circulation systems are stable and biotic crises often develop as a consequence of oxygen depletion. On land, niche-splitting, complex food web structures and general overspecialization of biota will occur. Whether the crisis is caused by a single anoxic event (e.g. in the Late Devonian) or a disturbance by an asteroid impact (e.g. the Cretaceous/Tertiary boundary), it will only trigger total collapse of an ecosystem if a large part of it was already in decline. The regulatory mechanisms and buffers are thermodynamically extremely efficient if they are given sufficient time in which to deploy their power. However, after major catastrophes the re-establishment of successful ecosystems will take millions of years. The present rate of sea level and associated temperature rise is much too fast to be compensated and buffered by the network of natural controls. It is likely that the transitional time towards a new steady state will be an extremely variable and chaotic episode of unpredictable duration.

Key words sea level change – global temperature increase – glacial episodes – greenhouse episodes – climatic buffers – extinction – carbon cycle – applied historical geology

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Preamble

This paper was written to present the topic 'sea level changes – processes and products' to a broader audience, both within and outside the geological and academic fields. We therefore apologize for simplifications and repetitions which might bother some colleagues, particularly those working in sedimentology and historical geology. We are also aware that we could not integrate all the data on modelling the future effects of greenhouse warming and related sea level changes, a topic which by itself would fill a volume of *Geologische Rundschau*. We nevertheless hope that this paper might encourage others to divulge more of our knowledge of the history of our planet and to take note of the lessons which might be learnt from it.

Prologue: the human race and sea level

In the short time since the beginning of the industrial revolution, the human race has caused sea level to rise by approximately 10 cm (Fig. 1). If such a change was detected in the geological record, most geologists would agree that something 'dramatic' or 'catastrophic' must have happened. They would eagerly look for evidence of disaster, destruction, or misery. However, it would be very hard for them to determine that an animal (and not the odd asteroid impact ...) was responsible for this global mess. For us, the actual polluters, exterminators and climate changers, this story is not even headline news. We wearily push away the facts which prove that sea level is rising and which tell us why this is so. Over the last 50 years sea levels have been rising at rates between 1.0 and 1.5 mm/year (Lambeck, 1990; averaged tide gauge data from the last 50 years indicate 1.2 mm/year). The rise parallels the global change of temperature and the increase in tropospheric CO_2 concentrations in the same period (Fig. 1). A connection with the global energy consumption is obvious. In 1989, the USA alone consumed 73370×10^{15} J, equivalent to 4.8×10^9 tons of CO_2, 37×10^6 tons of anthropogenic methane, and 130000 tons of Chlorofluorohydrocarbons (World Resources Institute 1992). Woelfli (1993) figures the annual global output of CO_2 from the burning of fossils fuels at 5 Gt.The hitherto existing trend of increasing temperature indicates a climatic sensitivity of 1.5 °C (meaning the increase in temperature accompanying the doubling of the pre-industrial atmospheric concentrations of CO_2; Fig. 2). By projecting this factor into the future, a 'business as usual' scenario predicts a global temperature increase of 2.5 °C from 1990 to 2100 (Fig. 3). A 'constant emission' scenario would still predict a temperature increase of 1.5 °C for the same period (Figs. 2 and 3). By maintaining the CO_2 growth rates of the early 1970s the concentrations of CO_2 will amount to more than 800 ppm in 2100; a level of 1 500 ppm will be reached after most of the fossil fuels have been burnt (Keir, 1991). Not considered in these predictions are the effects of other greenhouse gases (NO_x, N_2O, CO, CH_4 and other hydrocarbons), which already total about one-tenth of the global anthropogenic emissions (Goldammer, 1990). Carbondioxide concentrations of 1 200 and 800 ppm have been calculated for the Late Jurassic and Late Cretaceous, respectively (Ross et al., 1992; Caldeira and Rampino, 1990); at that time, however, the sea level was considerably higher than today ...

The oracle

Predictions of anthropogenic sea level changes

An increase in the greenhouse effect, in addition to many other implications, will rapidly destabilize the Antarctic shelf ice sheet. It will probably then result in the melting of the inland ice masses of the Alpine orogenic belt. However, a global increase in temperature should also cause an increase in precipitation from the circumpolar easterlies. It is therefore likely that for a limited period of time both the Antarctic and the Greenland ice sheets would grow rather than shrink, before general warming overcompensates this initial effect and causes the ice

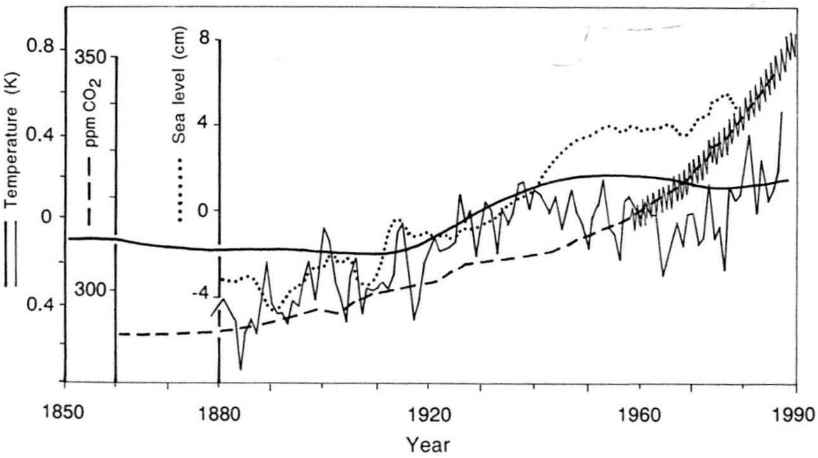


Fig. 1. Carbon dioxide concentration (in parts per million, broken line), sea level change as expressed by tide-gauge data averaged over five year periods (dotted line), global average surface temperature (light line) and secular surface temperature trend for the northern hemisphere (heavy line) plotted as a deviation from the mean. After Baggeroer and Munk (1992), Gornits et al. (1982), and Ghil and Vautard (1991)

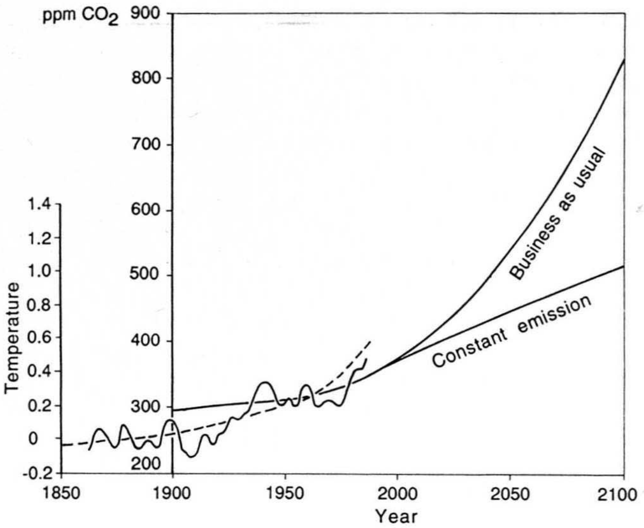


Fig. 2. The observed historical temperature change (deviation from the mean, in °C) agrees best with a climate sensitivity (meaning the increase of temperature accompanying the doubling of the pre-industrial atmospheric concentration of CO_2) of 1.5 °C (broken line, after Schlesinger and Jiang, 1991). Observed historical (Bach, 1984) and projected (Joos et al., 1991) atmospheric CO_2 concentration (in parts per million, solid line) for a 'business as usual' and a 'constant emission' scenario (the latter works under the premise that some of the excess CO_2 is drawn down into cold polar waters)

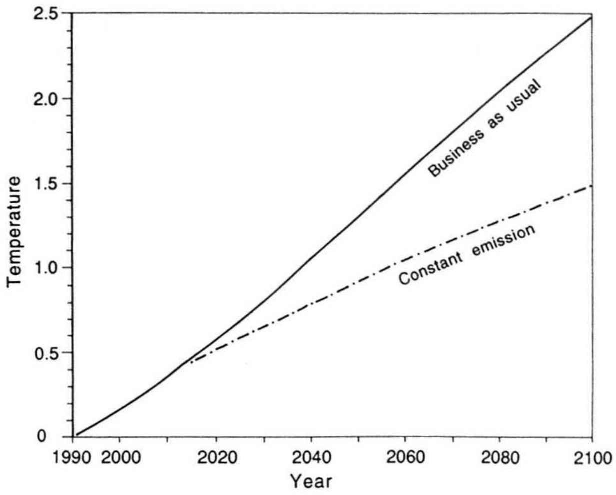
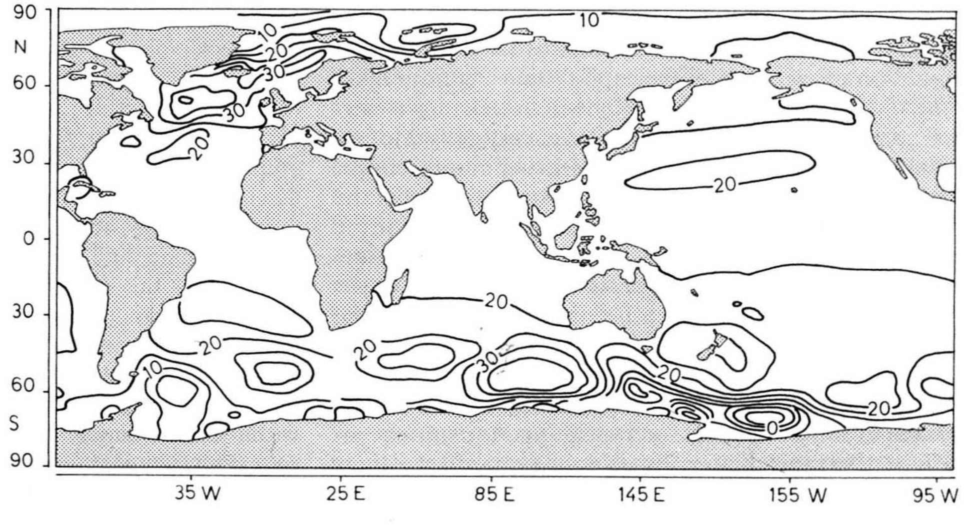


Fig. 3. Projected increase in average surface temperature (in °C) calculated for an increase in atmospheric CO_2 concentration in a 'constant emission' and a 'business as usual' scenario (after Schlesinger and Jiang, 1991)

covers to vanish. In detail, Meier (1990) and Lambeck (1990) give the following figures. (a) A decrease of the ice masses in the Alpine orogenic belt. Until now the melting of the glaciers contributed 0.5 mm/year to the rise in sea level. Projecting this rate to the year 2050 gives a sea level 0.16 m higher than in 1990. (b) Growth of the Greenland and Antarctic ice sheets may actually be responsible for a lowering of sea level by 0.45 mm/year (Greenland) and 0.6 – 0.75 mm/year (Antarctica), respectively. An extrapolation to 2050 would yield a sea level fall of 0.3 m compared with 1990. As the growing Greenland ice sheet would reach the coastline before 2050, enhanced marginal melting should account for a rise of 0.08 m. (c) Thermal expansion of ocean water will cause a sea level rise of 0.2 – 0.8 mm/year. This amounts to a rise of 0.2 m between 1990 and 2050. (d) Exploitation of continental groundwater resources results in a sea level rise component of <0.2 mm/year, producing a rise of 0.2 m between 1990 and 2050.

The current predictions calculate a net rise of sea level of +0.34 m (+/−0.42 m) until the year 2050 (Meier 1990). Figure 4 gives an idea of the anticipated rise in sea level following a doubling of CO_2. A rise of 30 cm would first affect lowlands such as The Netherlands or Bangladesh and would increase the risk of storm floods in areas such as the North Sea coasts. A serious hazard would be the collapse of the West Antarctic ice sheet; according to Lambeck (1990) and Blankenship et al. (1993), this would cause a global rise in sea level of 6 – 8 m. The total melting of the Antarctic ice sheet would produce a net rise in sea level of 60 m (Sudgen, 1992). Although most workers

Fig. 4. Loss and gain in the hydrosphere (expressed as a relative rise of sea level in centimetres) following the doubling of atmospheric CO_2 concentration in about the year 2050 (redrawn after Baggeroer and Munk, 1992). The plot is based on a coupled atmosphere-ocean model by Mikolajewicz et al. (1990). Continents are outlined with present day coastlines



consider total deglaciation as unrealistic, Barrett et al. (1992) pointed out that only about three million years ago there was an extensive deglaciation pulse on the East Antarctic ice sheet, which might be interpreted as an unstable response to climate warming.

Predictions of natural sea level changes

Owing to the ongoing continental collisions in the Alpine orogenic belt we actually live in a time of enlarging ocean basins and hence in a trend of falling sea level. However, millions of years are needed until these geodynamic processes create sufficient space to compensate for a rise in sea level caused by melting ice, which is actually taking place within a few thousand years. There are few natural process other than glaciation/deglaciation which are able to produce rapid sea level changes. Earthquakes in subduction zones with magnitudes >8.5 are known to cause spontaneous net reductions of the ocean volume (e.g. off Chile in 1960, 573 km^3; off Alaska in 1964, 250 km^3; after Bilham and Barrientos, 1991). This may result in single spontaneous sea level rises of up to 1.7 mm, which will be compensated for in the long term. As a natural healing process such earthquakes are counterproductive, and are not very desirable.

In summary, anthropogenic changes in the kryosphere-hydrosphere-biosphere-atmosphere system will definitely provoke a short-term change in sea level. Among the network of natural controls on our planet there is no mechanism other than glaciation which may compensate this rapid rise in sea level. As to the long-term consequences, we will later explain how, in the network of natural controls, a changing sea level may be coupled with climate.

A job for sorcerer's apprentices

Browsing through the recently published work on this subject and one single glimpse at the results of the 1992 United Nations Conference in Rio de Janeiro shows that there is no reason to believe that the behaviour of the human race will drastically change within the next few years. Chainsaw Darwinism will continue being very popular in the tropics, and burning fossil fuels is the very condition of existence of the capitalistic economy. Likewise, the trend of rising sea level will not change either. Eventually, mankind with a reduced energy consumption would be as helpless as a government without a budget deficit. This is why some scientists are used to predict the future. They are looking for the solutions which cause the least possible inconvenience and which at the same time ensure that money rolls in the right direction ('How the greenhouse can be staved off without giving in to the Greens', as Jones (1990) put it ironically in Nature). Among such possible 'solutions' are the fertilization of the Antarctic Sea with iron to extract CO_2 from the system by initiating plankton blooms and the subsequent fallout of organic matter. To yield the same effect, others had rather fertilize the sea with phosphates on a global scale. The direct injection of CO_2 into the oceans has also been considered. How about copying volcanoes and bringing out 'icehouse' aerosols (SO_2 or inert dust) into the stratosphere to increase the albedo and hence lower the global temperature? A serious step in this direction has already been taken through the emissions of jetplanes, which produce an annual increase of 5% in stratospheric sulphate aerosols (Hofmann, 1991). A measure of unrivaled cheapness would be to simply increase the combustions of our good old sulphure-rich coal; this would create the desired compensatory effect in the troposphere. The high-tech solution simply puts some aluminium shields in an orbit proximal to the earth. We could already do this for a bargain of US$ 20×10^{12}. The ultimate solution is to put a 2000 km diameter shield at the Lagrange point between the Earth and the Sun. For the thrifty developing world economies there is always the option of substituting burnt tropical forest by eucalyptus plantations. These fastgrowing forests have the great advantage of being less insect-infested and much more easily accessible for fertilizing and wood-cutting machinery; in addition, they could extract respectable 10 Gt of CO_2 per year from the atmosphere. Of course, this works only if we do not burn them up again but then, some responsibility should eventually remain with those living down there ... What really matters is that all these little games keep the northern hemisphere 'up' on the globe. Not surprisingly, the authors of a recent comprehensive study on this subject demand that research activities should continue under the heading of looking for flaws in the scheme, at least 'unless nasty surprises are assigned a zero probability' (Keith and Dowlatabadi, 1992). Good luck!

Unpleasant surprises arranged by nature

The earth is ready to offer 'nasty surprises' at short notice, even without our help. Drillcores from the Greenland ice sheet show that during the last ice age the temperature repeatedly increased by as much as 7 °C within a few decades, though without any recognizable periodicity (Johnsen et al., 1992). On the other hand, a single giant two-week volcanic eruption (Toba in Sumatra, 73 500 years ago) was probably the final catalyst for the beginning of the last Ice Age by the injection of icehouse aerosols into the stratosphere (Rampino, 1991; Rampino and Self, 1992). Although questioning volcanic aerosols as a likely cause of the onset of glaciation, Hay (1992: 307) points to a possible feedback mechanism between sea level, climate and volcanism: 'the increased flow of material in the asthenosphere in response to isostatic adjustments to sea level change and ice-cap loading [might cause] more intense volcanic activity during times of glaciation and deglaciation'. Obviously, the phenomenon 'sea level change' is but one of the many variables within the extremely complex network of natural controls. This network encompasses and interconnects the lithosphere, hydrosphere, kryosphere, biosphere and atmosphere. Our present knowledge of this system is still moderate. Nevertheless, we already know enough to be sure about one thing: the repair of our man-made problem with one of the tools out of the magic box of 'geoengeneering' will definitely bring an element of gambling into that system.

Sea level changes in geological research

Sea level changes of considerable amplitude are a fact in the history of the earth. It is also generally accepted that they represent a very efficient process in shaping the surface of the Earth. Nevertheless, only in the last two decades have earth scientists increasingly focused on this topic. Sequence stratigraphy, the theory of the continuous redistribution of sediments by relative or global sea level changes, is today one of the fundamental concepts of geology. Geologists now have a tool to better explain the spatial, temporal and compositional distribution of sediments on the known surface and to predict it in the subsurface. This has opened the way for an unexpected number of applications both in the practical field (hydrocarbon exploration) and in academic research (feedback of controlling factors; who controls whom?). As with other theories, a phase of scrutinity, checking, modelling and modification presently follows the initial enthusiastic acceptance. One of the symposia held with this intention was 'Sea level Changes – Processes and Products', a theme meeting performed in February 1992 by the Geologische Vereinigung at the University of Stuttgart; some of the papers presented at this conference are published in the present volume.

Frequency and scale of sea level changes

We know now with sufficient accuracy that sea level changes of various amplitudes and duration punctuate the geological history of the earth. A hierarchy of cycles has been established which shows the following orders of magnitude: 10^8 years (first order), 10^7 years (second order), 10^6 years (third order), 10^5 years (fourth order), 10^4 years (fifth order). Cycles of lower order are known but the available means of determination of geological ages allow a discrimination only in the youngest geological past. Cycles of the first and second order are known throughout the Phanerozoic (Fig. 5). Their actual position in the stratigraphic column has not changed very much since the original paper by Vail et al. (1977). The maximum amplitude ranges between +270 and −150 m compared with present day sea levels. Minus 130 m is considered a reasonable value for the last glaciation (Lambeck, 1990).

Recognition of sea level changes

A rise in sea level shifts the characteristic sedimentary coastal sand belt located between the terrestrial mainland and the shelf towards the continent. During such 'transgressions' eroded river valleys are flooded and become estuarine river mouths, leaving behind a backstepping cover of fluvial sediments. A geological section thus shows lowland fluvial deposits followed by coastal sands, which in turn are topped by commonly fossiliferous, fine-grained shelf sediments. Biostratigraphic correlation of the different sections eventually results in a palaeogeographic reconstruction. The amount of relative sea level rise can be measured if this reconstruction includes the position of the former coastlines.

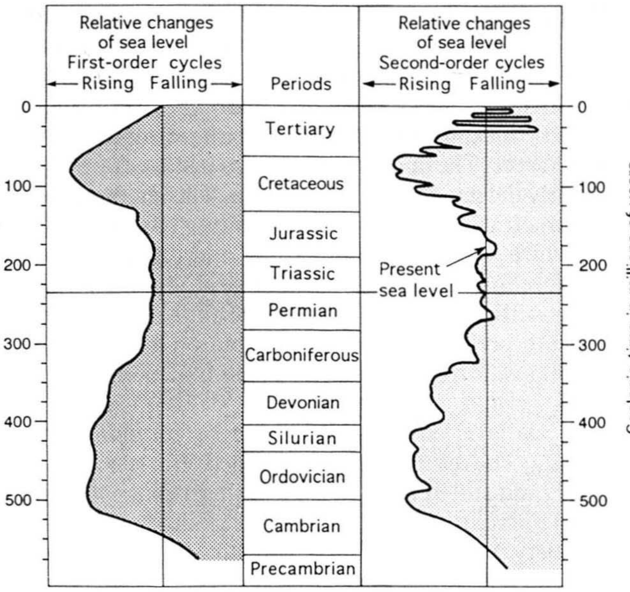


Fig. 5. Major sea level fluctuations (first and second order) for the Phanerozoic (after Vail et al., 1977; and Haq et al., 1988)

A falling sea level shifts the coastal sedimentary belt shelfwards. Such retreat of the coastline, termed 'regression', can be recognized when terrestrial sediments expand over formerly marine areas. Rivers will increase in length and will be forced to cut down into the shelf or coastal sediments deposited earlier. If the sea level drops considerably, erosion may propagate far into the hinterland, producing unconformities which cut fossil soils and fluvial or lake sediments. In the coastal areas deltaic river mouths will build up rapidly. Surplus sediments that cannot be stored on the shelf may bypass it in submarine canyons and eventually reach the deep sea through suspension loaded turbidity currents. There, the sediments form deep sea fans. This is especially true for a lowering of the sea level beyond the shelf edge. In this instance, not only the former terrestrial areas but also the former shelf are eroded and huge masses directly bypass towards the deep sea. A moderate regression usually results in a geological section in which coastal sands and fluvial deposits overlie shelf sediments, whereas a strong regression only leaves an erosional unconformity which truncates older marine sediments. If the age is known by the occurrence of relevant fossils, the geologist can again use the migration of diagnostic units such as the coastline to reconstruct palaeogeography and to calibrate the relative change of sea level.

The method is easily applied only when later processes, particularly erosion, have not removed major parts of the geological record. This is why geologists try to support their often poor surface information by subsurface data obtained through the reflection pattern of artificial seismic waves. The unconformities, for instance, are fairly accurately detected by such reflection. This method leads to a geometrical image of the architecture of sedimentary units, which is further substantiated and refined by data from borehole cores and geophysical borehole logs. Given a sufficient surface and subsurface database it is possible to predict the spatial distribution and sedimentary composition of deposits for given time periods. This method, seismic stratigraphy, also yields measures of relative sea level changes which can be compared with other data. The result of these combined efforts is a highly distilled (and still at least partly disputed) chart of global sea level fluctuations. For details, the reader is referred to the Society for Sedimentary Petrology Special Publication No. 42.

Causes of sea level changes

Theoretically, two different types of causes account for sea level changes: sea level fluctuations due to climatic change, which means, by a change in the volume of ocean water and sea level fluctuations caused by crustal movements of the earth, which lead to a change in the shape and volume of oceanic basins. As will be shown in the following, the two types cannot practically be clearly separated.

Climatic causes: glacio-eustatic sea level changes

The hydrosphere contains 1.4×10^{24} g of water. Of this, 96% presently fills the oceans, 2% forms ice and 2% represents groundwater, atmospheric water vapour, lakes and rivers. A total of 80% of the global ice or 65% of the global freshwater are concentrated in the Antarctic ice sheet. The total melting of the Antarctic ice would raise global sea levels by 60 m. Water fixed in sediments and swallowed in subduction zones is constantly redistributed to the hydrosphere by metamorphism and subduction zone volcanism, respectively. If such an equilibrium did not exist our oceans would be emptied within 15 million years. Hence, the growth and melting of the polar icecaps and inland glaciers represent the dominant mechanisms of changing the volume of the oceanic waters. Berger et al. (1990) calculate the total ice volume on the northern hemisphere at 27×10^6 km^3, responsible for a sea level drop of 70 m. The total ice volume produced by the last glaciations has been calculated from the total sea level drop (minus 130 m) at $51{,}3 \times 10^6$ km^3 (Marsiat and Berger, 1990). This kind of sea level changes is termed glacio-eustatic. With the exception of local, very short-term relative sea level changes caused by coseismic crustal movements, rapid global sea level fluctuations are believed to be of glacio-eustatic nature (Vail and Sangree, 1988; Haq, 1991); they may show rates up to 10 m per 1000 years, suggesting the collapse of climatic systems (Pitman, 1979). Such 'high frequency' sea level oscillations of the fifth order may be controlled either by short-term oscillations of solar irradiation (a very unlikely cause) or by autocyclic processes within the hydrological system of the earth. Additionally, cycles of $>$20.000 years and $<$400.000 years can be correlated with periodic astronomic changes ('Milankovitch cyles'), such as ecliptic and excentricity changes in the orbit of the earth (de Boer, 1991). After Berger (1988) and Berger et al. (1990), the fundamental periods of these cycles are 19000, 23000, 40000, and 100000 years (with the latter giving the strongest signal). Jacobs and Sahagian (1993) pointed out that small-amplitude sea level fluctuations associated with Milankovitch periodicities might be explained as a function of lake water storage, especially during episodes characterized by the existence of giant lakes such as the Triassic period. In cycles of higher order ($>$1 million years), however, processes other than glacio-eustasy increasingly contribute to sea level changes.

Tectonic causes: tectono-eustatic sea level changes

Plate tectonic processes cause changes in the shape of ocean basins as well as in the buoyancy of continents; naturally, this is reflected by sea level changes. Such tectono-eustatic sea level fluctuations commonly show cycles ranging from second to fourth order. Among possible causes are:

1. Changes in the spreading rate of oceanic crust. These changes are long-term and range between 0 and 20 cm/year. They cause first-order cycles of eustatic sea level changes. Oceanic crust built over a long period of time at high spreading rates forms a hot and hence bathymetrically elevated mid-ocean ridge which displaces a large volume of water onto the continents. The large timespan between the Late Jurassic and Late Cretaceous was such an episode of fast sea floor spreading which resulted in a very high sea level and extensive flooding of the continents. The buffer effect of this large sea surface, in combination with a high CO_2 level, produced a warm, equalized climate throughout this episode. During times of little spreading activity, on the other hand, the sea level is mostly low. Consequently, terrestrial areas are much larger; this results in a predominance of continental climates and favours inland glaciation, which in turn amplifies the trend of dropping sea level. Such a situation existed during the Permian, which was characterized by heavy glaciation in the southern hemisphere. The extreme climatic changes related with the highs and lows of first-order cycles are often termed 'greenhouse' and 'icehouse' episodes, respectively.
2. Changes in the buoyancy of continents. These may result in three ways. (a) 'passive' continental margins are linked with old, and hence cold and deep-lying oceanic crust, which causes a pull-down effect. The subsidence of such margins changes reciprocally with the spreading rates of associated mid-ocean ridges. (b) Changes in the mechanical coupling between subducted and overthrusted plates at convergent plate margins. High subduction

velocities often cause uplift of the overriding plate. Certain segments of the presently active continental margins or island arcs are held up in a position much too high for their average density, e.g. the Coastal Cordillera of northern Chile, the island of Cyprus or the Nicoya Peninsula in Costa Rica (which 'ought to' lie 3000 m lower than it actually does). (c) Converging stress fields around a continent. Africa, for instance, is mainly surrounded by divergent plate margins and thus lifted up more than 100 m above its 'normal' isostatic position.

Limits of the method

Both glacio-eustatic and tectono-eustatic factors interrelate in such a way that high frequency oscillations modulate the lower frequency oscillations. This results in amplifications, neutralizations or even reversals of a given trend. In other words, even during 'greenhouse' episodes regressions may occur locally or regionally, or, vice versa, transgressions are also possible during 'icehouse' times. If a shelf margin sinks faster than the global sea level fall, then a transgression will take place in this area despite the general sea level drop. Tectonic tilting of crustal segments also may have this effect. If the sediment input is out of phase with the sea level curve, the general trend can also be reserved. In very tectonically active regions such as active continental margins or island arcs, rapid and frequent vertical movements of crustal segments, together with intense volcanic activity result in a changing sediment input which may easily swamp the eustatic signal. Eventually, the above-mentioned strong earthquakes may damage not only humans and their buildings, but also sequence stratigraphy: The 7.5 magnitude earthquake on 22 April 1991 near Limón (Costa Rica) lifted the Caribbean coastline by 1.5 m, including a coral reef. The emergence of coral reefs, however, is considered one of the finest tools in the shop of sequence stratigraphy ...

In summary, it must be stressed that not every global sea level rise must ubiquitously cause a transgression, just as any eustatic sea level fall will not necessarily imply a world-wide regression. This is why the term 'relative change of sea level' is commonly preferred. As to the recognition of past sea level changes, this leads to certain procedures and requirements which have to be fulfilled before drawing any conclusion: (a) The interpretation of depositional environments must be carried out carefully and as detailed as possible to obtain reliable data on relief, climate and ecology. (b) The age determinations of analysed sediment successions must be as accurate as possible to enable the comparison of coeval materials and environments. Otherwise, the global cycle chart of HAQ et al. (1988) 'becomes a self-fulfilling prophecy' (Macdonald, 1991). At the moment, the best possible time resolution for the Mesozoic era is only of the order of 10^6 years (occasionally better); for the Tertiary it approaches 10^5 years, and only in the Quaternary is it between 10^4 and 10^3 years. (c) Local results must be compared with the corresponding regional and global database to eliminate local tectonic events.

In spite of these restrictions the knowledge of the run and extent of past sea level changes has rapidly increased within the last decade. There seems to be a general agreement that eustatic signals can be reliably identified whenever tectonic quiescence has allowed them to develop.

Sea level changes in an evolving world

In the earlier sections, we have already quoted some of the attempts which try to quantify the effects of modern greenhouse gases on climate, the environment and, hence, sea level. The problem with any climate prediction is that we do know most of the controlling factors, but we ignore the way in which they co-operate, just as we can only speculate if and when there will be a steady state. In the geological past, on the other hand, we know a lot of products, but we seldom possess more than qualitative data on the nature of the processes involved; most of these are recorded in sedimentary successions. Nevertheless, the quality of this evidence is of paramount importance for actual predictions, as the results of given processes are directly documented. Within certain limits, the former earth is comparable with the present at least since the Cambrian. The high evolutionary level of former organisms reveals that the atmosphere and the gaseous phase of the oceans were similar. Marine food webs also show comparable characteristics, whereas life on land is comparable only since the Silurian, when land plants increasingly conquered the continents. Sea level changes are known since the Cambrian and were certainly of major importance during the Precambrian era, which records at least two long glaciation periods. In the following, some examples from the history of the earth should explain the prediction abilities of an 'applied historical geology'.

High sea level as a climatic buffer

First-order cycles of sea level changes parallel long-term climatic changes. The global sea level was particularly low at the end of the Precambrian, during the Late Ordovician, at the transition from the Carboniferous to the Permian and from the Tertiary until the Present (Fig. 5). These episodes are characterized by the existence of polar ice caps and inland glaciation ('icehouse' episodes). The episodes in between correspond to phases of intense sea floor spreading: the opening of the lapetus ocean (the Cambrian to Ordovician ancestor of the Atlantic), opening of the Palaeotethys (a Silurian to Carboniferous circumequatorial seaway), opening of the Neotethys (the Mesozoic circumequatorial seaway), and of the Atlantic Ocean (with maximum spreading in the Cretaceous and Tertiary). During these episodes, global sea level rose and oceans 'spilled over' onto the continental mainlands. The geological record reveals that these times of high sea level were characterized by an equilibrated climate, general warming and the disappearance of polar and inland ice caps ('greenhouse' episodes). Two possible mechanisms can account for this. (a) 'maritime' greenhouse effect: widespread shallow shelf seas have an equilibrating effect on the climate by their capacity to act both as a thermal buffer and by evaporating larger amount of the weak, though very common, greenhouse gas water vapour. (b) 'volcanogenic' greenhouse effect: degassing of volcanic CO_2 and H_2O is positively coupled with spreading and subduction rates. The atmospheric CO_2 concentration in the Cretaceous greenhouse is estimated at 1200 ppm (Ross et al., 1992), whereas during the Last Glacial Maximum (18000 years B.P.) it has been as low as 200 ppm (Adams et al., 1990). As accelerated volcanic activity also existed during some icehouse episodes (e.g. during the Permian), the 'maritime' effect (climate buffering through sea level rise) seems to be the more important control in the long term. The ultimate cause, of course, lies in the plate tectonic processes which continuously level up what climate levels down.

The Cenozoic icehouse episode or how many roundabouts create an ice age?

The oxygen isotope record of the Cenozoic suggests that permanent ice began to accumulate 50 million years ago and that ice volumes equivalent to the present have existed for 40 million years (Prentice and Matthews, 1988; Hay, 1992). However, Barrett et al. (1987) put the onset of Antarctic glaciation at 36 million years. Thus the youngest of the earth's icehouse episodes has already lasted more than 30 million years; it includes the Present despite the actual global temperature increase. Especially from the Quaternary onwards, alternations of cold and warm episodes (glacial and interglacial stages) are known in great detail. Milankovitch orbital cycles may be 'the pacemaker of the ice ages' (Hayes et al., 1976), but are certainly not the ultimate cause of glaciation. Energy balance models for the earth (North and Crowley, 1985) have confirmed that an earth climate with small ice caps is 'inherently unstable' and that in the long term the climate reverts to the stable glaciated or unglaciated states (Hay, 1992). As to the causes of glaciation, Hay (1992) gives six possibilities: (a) changes in the composition of the atmosphere; (b) increased aerosol content of the atmosphere; (c) vertical movements of the earth's crust; (d) changes in atmospheric circulation; (e) changes in sea ice cover; and (f) changes in oceanic circulation. The Cenozoic icehouse episode most probably resulted from positive feedback among these factors as discussed in the following.

With Australia drifting away from Antarctica since the Eocene, a circumpolar ring current developed which cooled the entire continent and initially provided the moisture necessary for the growth of an inland ice cap. The south polar ring current, aided by the rapidly increasing ice cap, was responsible for the development of the psychrosphere, the cold bottom water layer which characterizes our present oceans. Derived from the cold polar seas and flowing bottomwards towards the equator, these cold waters well up to the surface at the western sides of the southern hemisphere continents, where they cause intense regional cooling and the formation of coastal deserts, even in low latitudes. At the North Pole, on the other hand, sea ice cover could not yet have been formed, as water has a higher thermal buffer effect than a continent. The rapid opening of the North Atlantic Ocean, however, opened connections such as the Denmark strait, thus allowing Arctic water to overflow and to contribute further to the development of the psychrosphere. The trigger for northern hemisphere glaciation was the closure of the Isthmus of Panamá between 4.2 and 2.4 million years ago (Keller et al., 1989), caused by the growth of the south Central American island arc system and its drift into the gap between Colombia and northern Nicaragua (Seyfried et al., 1991). The closure initiated the formation of a convection cell in the north eastern Caribbean, which until today drives the Gulf Stream, bringing warm water towards the north and with it the moisture necessary for the glaciation of Greenland, the Baltic shield and the Arctic Sea. Meanwhile, mountain building at moderate and high latitudes all over the northern hemisphere uplifted many young mountain ranges (the Rocky Mountains, the Alps and the Himalayas). These large uplifts altered the atmospheric circulation to an extent that quasi-stationary Rossby waves could develop, which in turn provided the regional circulation pattern necessary for feeding moisture onto the continents (Hay, 1992). Raymo and Ruddiman (1992) pointed out that young large uplifts such as the Tibetan Plateau, withdraw considerable amounts of atmospheric CO_2 by intense chemical weathering, by providing enormous exposures of silicate rocks near a warm ocean. Today, 25% of the total dissolved load reaching the oceans comes from this plateau which represents only 5% of the total continental area. According to Hay (1992), such a tectonically driven CO_2 depletion could play a 'possibly decisive role in the transition from an ice-free to a glaciated earth'.

The icehouse of the late Palaeozoic: a concomitant effect of the formation of the supercontinent Pangaea

Extensive continent-continent collisions in the course of the closure of Palaeotethys created the supercontinent Pangaea which, with the exception of parts of south-eastern Asia, reunited all continents of the earth. The spreading rate of the oceanic crust was low; sea level was about as low as at present. The fixation of CO_2 through the widespread formation of coals during the Carboniferous was an additional step towards the coming icehouse. Glaciation of the South Pole was easily achieved as the Pole was wandering between southern South America, South Africa and Antarctica, producing the so-called Gondwana glaciation. The North Pole was first positioned in the sea, later in Siberia and then also underwent extensive glaciation. The enormous size of this supercontinent and the low sea level prevented general climatic buffering by the sea. Actually, the term 'icehouse episode' is somewhat misleading: the difference between this and a 'greenhouse'-type climate is not globally lowered temperatures but rather strongly accentuated climatic differences. The Permian period was not only characterized by enormous glaciation at high latitudes but also by gigantic (possibly the largest ever existing) deserts and extensive evaporitic basins.

Sea level and biotic crises

The history of the earth is punctuated by numerous large and small biological crises, which affected either major parts of entire ecosystems ('species extinctions') or the populations of certain species ('mass mortality'). Many of these crises are related to cooling phases and hence to times of falling sea level. Species adapted to formerly hot low latitudes (such as the reefal organisms) were often the first victims of such cooling, as escape into areas as hot as before was not possible. For instance, many animal groups dwelling in shallow warm shelf seas became extinct during the Late Ordovician, the so-called 'Sahara Ice Age'. The Gondwana glaciation of the Permian had even more pronounced effects. Another extinction caused by cooling occurred at the end of the Eocene, when cold bottom waters derived from the poles developed again after a very long time.

In addition, global extinction and mass mortality events occurred which were apparently initiated by the warming trend accompanying rising sea level. This is possibly true of the Late Devonian, where coral reefs in particular vanished on a global scale, despite a continuing, warm climate comparable with or even warmer than that of today (cf. Gao, 1993). The reason, however, is not a drowning of these shallow water, highly productive ecosystems. As the rapid and extremely strong sea level fluctuations of the last ice age clearly prove, reefs can keep up with practically any rate of sea level rise due to their rapid upward growth (according to Chappell and Polach (1991), coral reefs easily coped up with a rapid sea level rise of 50 m at the end of the Younger Dryas event some 11 000 – 10 000 years ago). What were fatal for these ecosystems were other unfavourable developments which may accompany sea level rise. As has already been mentioned, a rising sea level causes a buffering of climatic differences. Arid climates become more humid and the temperatures of high and low altitudes approach each other. The waning or disappearance of polar ice caps reduces the circulation of cold oceanic bottom waters, stops upwelling at the western coasts and is responsible for much weaker wind systems. This in turn strongly lowers the global water circulation and water exchange in the oceans (cf. Berger, 1991). Many marine regions will suffer from oxygen depletion, causing partial or total collapse of marine ecosystems. As a result, black shales develop within the zone of oxygen depletion of the oceans (cf. Fischer and Arthur, 1977). The demise of the Devonian reefs is associated with bituminous deposits covering these structures. In the Rhenish Massiv, the Late Devonian Kellwasserkalk is such an example. Hence climate, marine circulation systems and sea level can interact in a way which leads to elevated nutrient concentrations, oxygen depletion and finally the extinction of most of the highly vulnerable reef corals. After the Late Devonian black shale death, the few remaining corals needed almost 150 million years of development to recover their reef building ability. It should be noted that some workers relate the Late Devonian biological crisis to the impact of an asteroid, but in our opinion there is no convincing evidence for this.

Signs of fatigue at the end of a long greenhouse episode

The biological crisis at the end of the Cretaceous period about 65 million years ago became very popular through the show piece of dinosaur extinction. There is increasing evidence that a huge asteroid, which possibly measured 10 km in diameter, impacted in the area of the Yucatán Peninsula (Mexico). However, it is also known that many groups of organisms had already died out some time before this event. At the end of the Cretaceous, the earth had undergone a 100 million year long greenhouse episode, which by its great length had stabilized the entire biological and hydrological system of our planet. An extremely differentiated global ecosystem developed which was eventually overadapted by niche splitting, and whose abilities to rejuvenate and diversify were simply used up. With the impact of the asteroid and the following 10 years of winter the biosphere collapsed. The subsequent radiative adaption, that is, the explosive development of new species, reestablished the innovative capability of the biosphere by creating other more resistant ecosystems headed by more modern groups such as the mammals and grasses.

Sea level and fossil fuels

Regional or global black shale events are commonly correlated with high sea levels throughout the entire history of the earth. In a warm and thermostratified ocean black shales form more readily than in a cold ocean although the latter is more productive due to a higher input of nutrients and better recycling (cf. Berger, 1991, Berger and Wefer, 1992; see below). As has been explained in the section on biotic crises, black shale events mostly resulted in the mass mortality of populations of highly specialized shallow water organisms rather than in regional or global species extinctions. One hydrocarbon source rock has been extensively studied as it represents the most important source rock in the North Sea area: the Kimmeridge Clay. This black shale was deposited during a maximum highstand of sea level during the Late Jurassic, which was an epoch of generally high sea level and well balanced climate. During Late Jurassic summers, low atmospheric pressures must have existed even in the North Pole region (see Fig. 6; Oschmann, 1990). This suggests a marked climatic stabilization, particularly in the northern hemisphere, and is in strong contrast with the present situation which is characterized by high

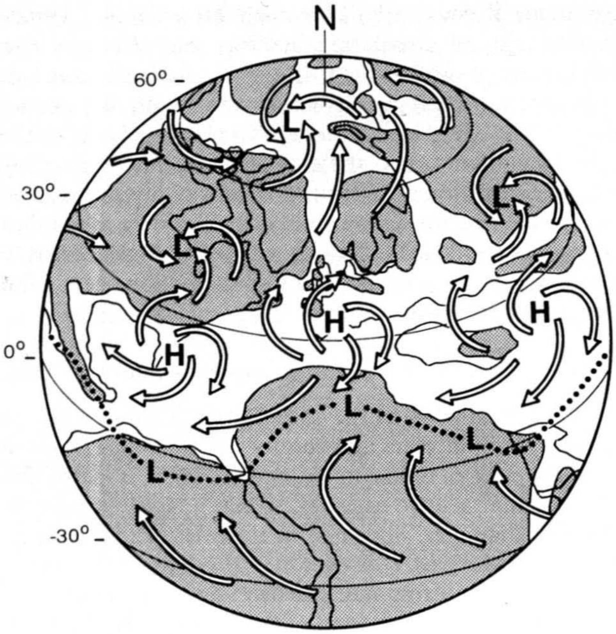


Fig. 6. Weather forecast for a warm Late Jurassic summer day. Outline of present continents, solid line; past continents, stippled areas; oceans, blank; barometric highs and lows, H and L. Note the existence of a low pressure field around the North Pole (simplified after Oschmann 1990)

atmospheric pressures in the polar region, causing cold deserts. For the Kimmeridgian, Valdes and Sellwood, (1992) modelled the following climate: average surface temperature 20 °C (presently 14 °C), average cloud cover 72% (presently 55%) and average precipitation 2.6 mm/day (today 2.3 mm/day).

Coal swamps, the other important source of fossil fuels, preferrably form during the transition from a high to a low sea level regime. It seems that the onset of glaciation after a long greenhouse episode is important for the formation of paralic coals since it commonly comes along with frequent small amplitude sea level oscillations. Both the Late Carboniferous and the Tertiary peaks in coal formation coincide with such scenarios, although coals also formed in a wide variety of climatic and regional settings at other times.

Sea level and reefs

A working group at Stuttgart Institute led by one of the authors (R. Leinfelder) is currently examining different reef types of the Late Jurassic seas. It was discovered that the 'reef' ecosystem may respond fairly flexibly to even severe ecological stress accompanying sea level change by simply changing from one compositional type to another. Under certain conditions and by accepting a drastic depletion of species diversity, reefs may even escape the 'black shale death'. In falling sea level regimes, reefs are commonly restricted to very shallow, wave-agitated seas and mainly develop as coral reefs; high sedimentation rates commonly hamper reefal associations in deeper waters. In rising sea level regimes, however, due to the retention of clastics in the flooded areas, reef systems are able to cover a much broader bathymetric range. In the Late Jurassic, shallow water coral reefs are often supplemented by reef associations composed of siliceous sponges and microbial mats, which colonize the deeper shelf. However, the climatic levelling coupled to major transgressions often led to partial oxygen depletion even in fairly shallow water so that the growth of 'normal' reef types stopped. Under these conditions, a reef type developed which is almost exclusively composed of microbial calcareous crusts, but which is comparable in size with its high diversity relatives (Leinfelder, in press; Leinfelder et al., in press; see Fig. 7). This is another example that the environmental changes accompanying sea level change need not necessarily cause global catastrophes for all groups of organisms, but rather puts selected, isolated ecosystems under stress.

Sea level and the carbon cycle

Sea level changes and related climatic changes of higher orders are obviously dominated by plate tectonic processes. However, the causes of sea level fluctuations of shorter duration and lesser extent are mostly of a very complex nature. To date, the CO_2 buffer capacity of oceans, reefs and carbonate platforms, as well as of terrestrial forests and tundra systems, is far from being fully understood. It seems that all of these may act both as sources and sinks for carbon and are hence powerful climatic buffers. The fixation of carbon in the living matter of terrestrial plant ecosystems represents a short-term or, if coal is produced, a long-term sink, whereas recycling of carbon in the soil is a carbon source, both of which may or may not be balanced (cf. Oechel et al., 1993, Smith and Shugart, 1993). The biologic pump, i.e. the production of organic matter in the photic zone and its partial extraction from the shallow water by sedimentation is considered to represent a major carbon sink (Berger, 1991; Wefer, 1991). However, the connection with sea level change is differentiated. The cold ocean of a low sea level scenario generally is more productive than a warm ocean of a high sea level regime (Berger, 1991). This is due to the increased input of nutrients and better recycling by deep ocean mixing during low sea level, whereas a high-sea level ocean is commonly called "hungry". On the other hand, higher productivity does not necessariliy mean more extraction of organic carbon by the biologic pump, since a lot of particulate organic matter sinking in downwelling areas is oxydized and recycled during the journey to upwelling areas. There, CO_2 is finally extracted by permanent sedimentation of organic matter. Thus, in a cold ocean, the biologic pump helps keeping atmospheric CO_2 values low. In a regime of rising sea level, on the other hand, the pump might be less effective initially, giving rise to an increase of atmospheric CO_2. At the final stage of an episode of rising sea level, the tendency of a warm ocean to be severely thermostratified

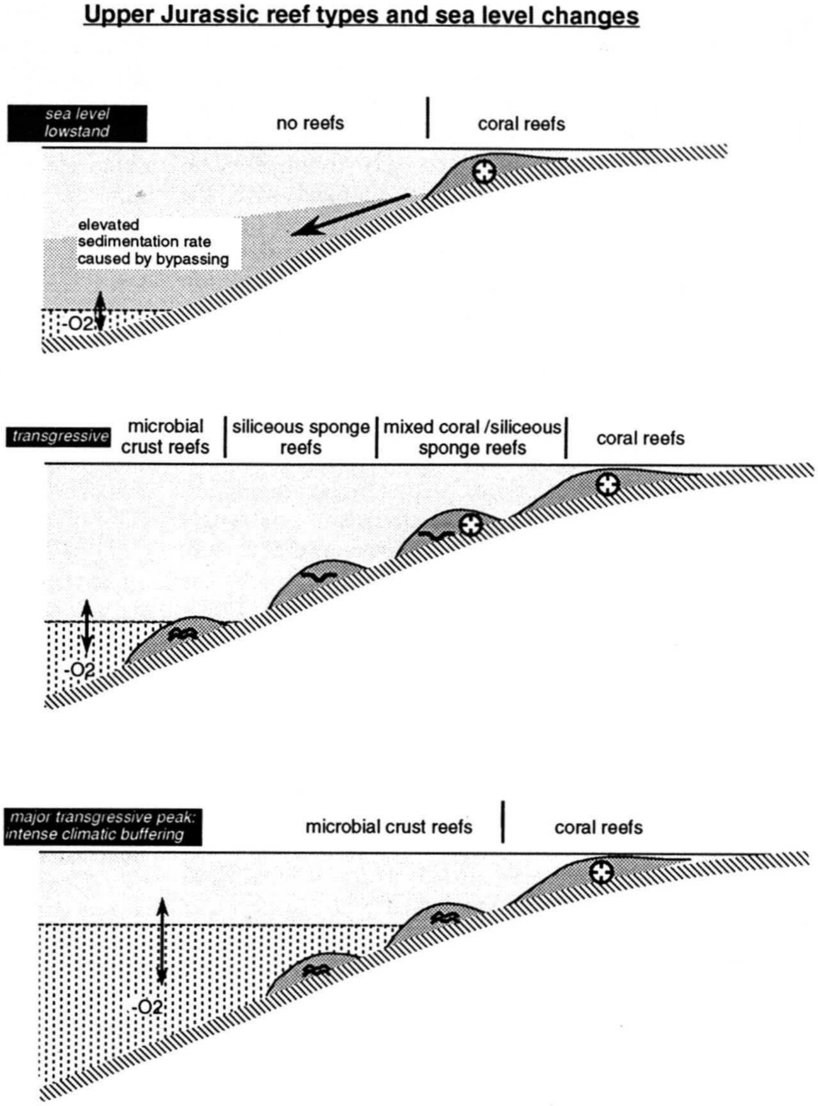


Fig. 7. The distribution of different benthic associations from Upper Jurassic reefs of Spain and Portugal is partly controlled by sea level and related climatic changes. During periods of low sea levels (top) coral reefs only grew in agitated water. In deeper water, a high sedimentation rate prevented reef growth. During rising sea levels (middle) sedimentation was reduced and different reef types grew at different depths. Extreme transgressive peaks (bottom) could cause additional climatic stabilization leading to a decrease in water exchange and a rise of dysaerobic waters. Microbial reefs were adapted to such moderate oxygenation and outcompeted other reef types during such phases (simplified after Leinfelder, in press and Leinfelder et al., in press)

increases the danger of collapse and hence the probability of regional black shale events. Such events will cause again a distinct drop of atmospheric CO_2.

The way in which carbonate platforms react is even less clear. In coral reef systems, the fixation of carbon in organic matter is fairly low (net production about 20×10^{12} g C_{org}/year), whereas the biologically mediated 'inorganic' precipitation of limestone is a significant term in global carbonate budgets (Crossland et al., 1991). Coral growth both fixes carbon in the calcareous skeleton and releases CO_2 into the water. Hence, in the short term, waters above living coral reefs do not become depleted but enriched in CO_2. For each mole of CO_2 deposited as carbonate, 0.6 mole of CO_2 is released into the shallow water and, due to changing pH, eventually into the atmosphere (cf. Ware et al., 1992). However, the same values show that in the long term CO_2 is actually extracted from the short-term carbon cycle by deposition as carbonate rocks. Hence the growth of coral reefs obviously displaces some of the CO_2 stored in the ocean waters both into the atmosphere and the lithosphere. Microbial carbonates are common in the peritidal areas of carbonate platforms and might actually represent an important carbonate sink. The karstification of carbonate platforms is another complicated buffer system: CO_2 stored in limestone is released, but this needs the draw-down of atmospheric CO_2. Both the limestone CO_2 molecule and the atmospheric CO_2 molecule first remain dissolved within the hydrosphere, leading to a short-range extraction of CO_2 from the atmosphere. The degassing of karst waters rich in CO_2 at springs or waterfalls, however, may directly redistribute parts of the dissolved CO_2 into the atmosphere. In the long term, much of the CO_2 from karstification is stored in the oceans, where it may or may not be released to the atmosphere. Estimates on the present short-term (annual) carbon budget give a clue to the buffer capacity of the oceans: the 8 Gt of carbon produced per year through the burning of fossils fuels (5 – 6 Gt C/year) and clearing of forests (2 Gt C/year) are thought to be compensated by incremental storage of 4 Gt C/year in the atmosphere, 2 Gt C/year in the biosphere and 2 Gt C/year in the oceans, the latter of which is a rough, uncertain estimate (Baggeroer and Munk, 1992). After Woelfli (1993) the atmosphere actually contains 720 Gt of carbon (in the year 1800, it may have contained only about 600 Gt); from there, 65 Gt are annually exchanged with the biosphere, which contains a total of 2000 Gt of carbon, and 78 Gt are annually exchanged with the ocean, which contains a total of 38000 Gt of carbon; sediments contain as much as 72000000 Gt of carbon, but exchange only 0.2 Gt per year with the ocean by erosion or sedimentation. Hence, the deep water of the ocean is the largest open reservoir of carbon containing about 35×10^{15} tons of carbon. The CO_2 content dissolved in the oceans is roughly 60 times higher than the atmospheric CO_2 content (Broecker and Denton, 1990). On the other hand, the storage of carbon in the deep ocean is strongly dependent on water temperature. This means that as long as the temperature does not change, exchange with the atmosphere will be strongly delayed (Woodwell, 1990). What will happen if due to climatic levelling the cold, gas-rich psychrosphere disappears? Will we have a retarded, but eventually catastrophic transfer of the CO_2 into the atmosphere? Or will the biological carbon pump be more active and help to form black shales?

It cannot even be ruled out that fluctuations in sea level and climate are forming a nearly closed-circuit, backfeeding subsystem. A simplified, not yet quantifiable model could be as follows. Rising sea level eventually leads to global black shale deposition caused by the decrease in marine water circulation. An enormous amount of CO_2 is extracted from the direct carbon cycle by this process because deposited organic matter is buried by sediments. The resulting decrease in the greenhouse effect leads to climatic accentuation, initiation or the accelerated growth of polar ice caps and hence to a sea level fall. Drawdown of atmospheric CO_2 in cold high latitude waters (open CO_2 window, cf. Berger, 1991) and extraction of carbon in upwelling systems will support this process. Increasing consumption of CO_2 by weathering of emerging silicate-rich rocks (Raymo and Ruddiman, 1992) and karstification will first also help removing atmospheric CO_2. This removed atmospheric CO_2 as well as the CO_2 released from the limestone will however, be transported into the ocean by rivers and will cause an increase of the pCO_2 in the shallow-water. This will eventually result in the release of CO_2 into the atmosphere, which might be the start for a new climatic warming and associated sea level rise. Once the wider shelf seas initiate the 'maritime greenhouse effect', the climate will be stabilized, the psychrosphere will gradually dissappear, the CO_2 window will be closed, and CO_2 will be increasingly released to the atmosphere. The growth of carbonate platforms will act as a buffer system, keeping the system stable for a longer period of time. However, prolonged stabilization of climate and ocean circulation might eventually cause a black shale event and everything will start once again. Whether this simplistic model works or not cannot be decided to date. First- and second-order sea level changes are clearly driven by plate tectonic movements; however, sea level fluctuations of lower order might be governed this way, at least to some extent.

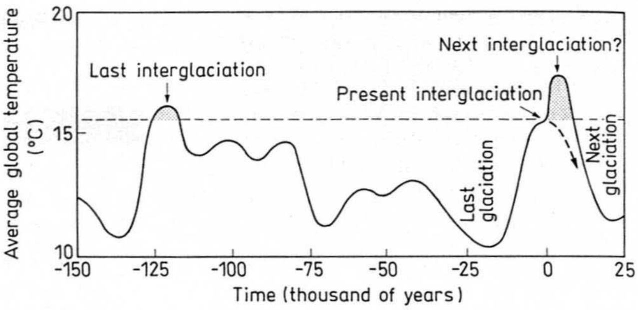


Fig. 8. Climate during the last 150000 years and its possible projection 25000 years into the future (after Imbrie and Imbrie, 1979). According to Campo et al. (1990), the difference in average global temperature between glaciations and interglaciations is in the order of 3–4 °C. Lambeck (1990) puts the last deglaciation between 18000 and 6000 years before present. Anthropogenic increases in atmospheric CO_2 concentration may lead to a super interglaciation, which delays the backset to another glaciation. Without taking anthropogenic influence into consideration, Berger (1988) predicts a slow cooling within the next 5000 years, an episode of amelioration after 15000 years, a cold interval after 23000 years, and the onset of the next glaciation after 60000 years

Conclusions

The first lesson to be drawn from the understanding of the role of sea levels in the history of the earth is a lesson in modesty: sea level changes and related climatic changes are components of a global network of natural controls interconnecting the hydrosphere, kryosphere, biosphere and atmosphere. For the time being, the interactions between controlling factors as well as the autocyclic, self-regulating nature of many processes can only be described in a qualitative manner, if at all. Any interference with this system will increase the probability of a chaotic reaction. Our present behaviour does not differ very much from that of the promoters of DDT in the late 1940s, who resorted to the extreme of eating spoonfuls of pure DDT in an effort to prove how harmless it is.

The second lesson is the realization that natural changes on the earth's surface happen so slowly that they alone would neither endanger the survival of (the anyway highly adaptive) human race, nor the existence of the present ecosystems, even considering the next few hundred years.

The third lesson is that the regulation and buffering mechanisms on earth are manifold and powerful, but limited in their elasticity. If a buffer (say the CO_2 consumption capacity of the oceans) is strained to its limits, the change towards a new stable state may possibly take place very rapidly and chaotically.

The fourth lesson is that the earth is currently in an icehouse episode. The present sea level is very low, polar ice caps are large, the Arctic Sea is glaciated and the spreading speed of the ocean floor is moderate. Have we already reached the end of the Cenozoic icehouse episode or do we still live in an interglacial stage (see Fig. 8)? The risk of rapid (perhaps chaotic) changes in such a situation is already rather high.

The fifth lesson is that until recently the CO_2 buffer systems of the earth were in optimum condition: rain forests, reefs and carbonate platforms had an enormous capacity in fixing and releasing CO_2 according to supply and demand. If we continue to destroy rain forests and reefs, we will very soon have deprived ourselves of a reliable and very efficient natural control mechanism.

The sixth lesson is that the CO_2 concentration of the atmosphere is presently moving towards values known for the greenhouse episode of the Mid-Cretaceous, characterized by a far higher sea level than today. In response to that increase, the sea level is already perceptibly rising. Will the rising seas heat up the greenhouse by additional evaporation of water (as water vapour already accounts for almost half of the present greenhouse effect; Chahine, 1992) or will the drawdown of atmospheric CO_2 into cold oceanic waters give us another reprieve? Will reefs die the 'black shale death' when the buffer capacity of the oceans is exhausted? Will the greenhouse effect then rise exponentially? At the moment, we can do nothing but define these questions.

Epilogue

Is this all only a storm in a teacup? Will there be no serious rise in sea level at all, as anthropogenic SO_2 in the stratosphere will have a compensatory effect? Or would some climatic levelling not be welcome anyway, because a higher precipitation rate, say in the Sahel zone, could be the solution to many of our problems?

One thing is fore sure: the relations between processes and products are far too complex as to allow an exact, regional or temporal prediction of sea level rise and climatic change. The flooding of lowlands such as Bangladesh, Florida, The Netherlands, or northern Germany is a serious threat, albeit only in the long term. However, would this be an acceptable price for the fecundation of the Sahara or the defrosting of the Siberian permafrost soils? Which conflicts would result from the ensuing migration of nations? What would happen in the unlikely event of the flooding of the Isthmus of Panama? Would the Gulf Stream disappear? If so, Central Europe would not become warmer, but colder and dryer.

We also can be certain that a general climatic change towards a new steady state would not be a snug, pleasant affair with the prospect of us lying under palm trees on an Alaskan beach, but instead an extremely variable and chaotic episode of unpredictable duration. Before the present circulation systems could decline and new, stable systems replace them, much stress would have to be tolerated.

We may turn a blind eye like the notorious German car drivers who publicly confess: ‚Mein Auto fährt auch ohne Wald'. But even these people should be aware that the earth does not need car drivers to maintain its existence. Looked at closely, neither the earth nor its biosphere needs us. Perhaps they are already patiently waiting for another species to run 'into the trap of too much success' (Martin, 1992), anticipating the next mass extinction, enjoying the prospect of another refreshing adaptive radiation, when new species will be on the run …

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